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STRATEGIC AIR COMMAND  
CONTRAIL FORMATION STUDY

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**ABSTRACT**

To investigate trends in contrail formation, military aircraft reports of contrail occurrence and non-occurrence were collected from 1 May 1990 to 30 April 1991. Over 4,800 contrail reports were collected and analyzed. Below 40,000 feet, 25.5 percent of the reports were occurrences, and above 40,000 feet, 64 percent were occurrences. The data confirms the dependence of contrail formation on ambient temperature and moisture. Results suggest previous formation theory is limited in scope and requires review. Data indicated the presence of "warm contrails". Results also suggest the potential for an improved forecast capability by incorporating synoptic-scale vertical motion into the contrail forecast algorithm. Between -46°C and -49°C, the verification rate for occurrences using current contrail forecast techniques was 21 percent. However, analysis indicates contrails formed in this temperature range 69 percent of the time when synoptic-scale upward motion was present. This study focuses on contrail formation below 40,000 feet; additional study is required to understand formation and optical properties of contrails above 40,000 feet.

**1. INTRODUCTION**

The prediction of exhaust condensation trails (contrails) is a vital component of weather support to USAF strategic aircraft. Accurate forecast of contrail formation areas is crucial to preserve tactical surprise and improve survivability of military aircraft. Appleman (1953) suggests contrail formation is dependent on ambient temperature, pressure, and relative humidity. Figure 1 shows the results of his work and is the contrail forecast concept used by Air Force forecasters today. The objective of this study was to evaluate the accuracy of Figure 1 as a forecast tool and examine potential for improvement using alternative forecast methods.

**2. DATA COLLECTION AND ANALYSIS TECHNIQUES**

To investigate trends and sensitivities of contrail formation, military aircraft (KC-135, RC-135, B-1B, B-52 and U-2) reports of contrail occurrence and non-occurrence were collected from 1 May 1990 to 30 April 1991. Aircraft reported time and date of observation, pressure altitude, corrected outside air temperature, latitude, longitude, and contrail condition. The one year data collection effort resulted in more than 4,800 contrail reports. Ninety percent of the reports were below 40,000 feet.

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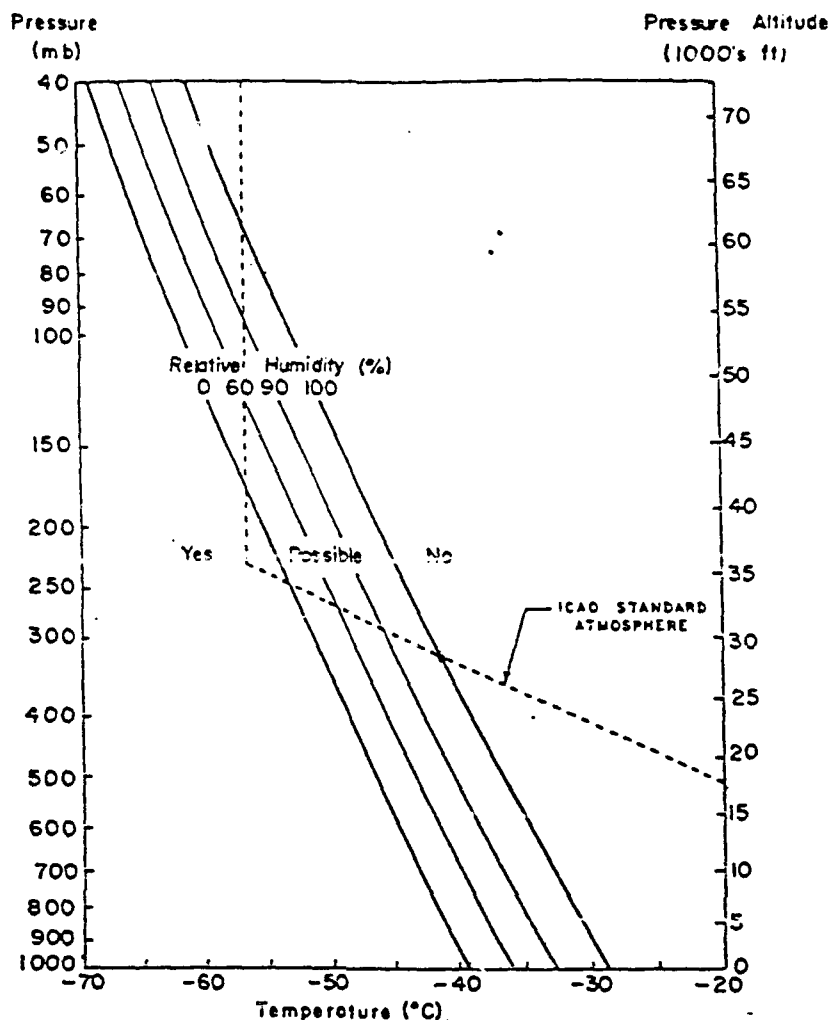


Figure 1. Contrail forecast chart. Chart uses relative humidity, temperature and pressure to forecast contrail formation. (After Appleman, 1953).

All reports were reviewed for meteorological consistency. If the pressure altitude and the outside air temperature were not consistent, a dry adiabatic assumption combined with the use of the standard atmosphere for altitude was used to correct the temperature. The 300 mb chart that best coincided with report time was most often used as an initial reference point for the temperature correction when needed.

The reports were entered into an ASCII-formatted database. The data were analyzed for trends and sensitivities using temperature, altitude, vertical motion, and combinations of the three as key parameters. The sign of the vertical motion was estimated using the 300 mb trough-ridge pattern. Upward motion was assumed to exist between the base of a trough and the apex of the upstream ridge. Downward motion was assumed to exist between the apex of a ridge and the base of the upstream trough.

### 3. RESULTS

The results in this paper are limited to data below 40,000

feet.

### 3.1 ALTITUDE SENSITIVITY

Figure 2 shows that as altitude increases, percent frequency of contrail formation increases. The seasonal data suggest the percent frequency of contrails is greater at lower altitudes for the winter and spring compared to summer and fall. The overall results indicate contrail formation frequency of greater than 50 percent does not occur consistently below 35,000 feet.

### 3.2 TEMPERATURE SENSITIVITY

Results of the temperature sensitivity are shown in Figure 3 for temperature range from  $-10^{\circ}\text{C}$  to  $-65^{\circ}\text{C}$ . From Figure 1, when the temperature is  $-40^{\circ}\text{C}$  and warmer and the altitude is greater than 25,000 feet, one would expect no contrails. However, the SAC contrail data documents the existence of contrails in this region. These contrails are referred to as "warm contrails". Between  $-10^{\circ}\text{C}$  to  $-19^{\circ}\text{C}$ , only extremely isolated instances of contrail occurrences were reported. As temperature decreases, percent frequency of occurrences increases slowly from 8 percent in the  $-20^{\circ}\text{C}$  to  $-29^{\circ}\text{C}$  range to 12 percent for the  $-30^{\circ}\text{C}$  to  $-39^{\circ}\text{C}$  range. As temperature continues to decrease, the percent frequency of contrail occurrence increases dramatically, reaching 73 percent at  $-51^{\circ}\text{C}$ . Below  $-51^{\circ}\text{C}$ , the percent frequency remains above 70 percent.

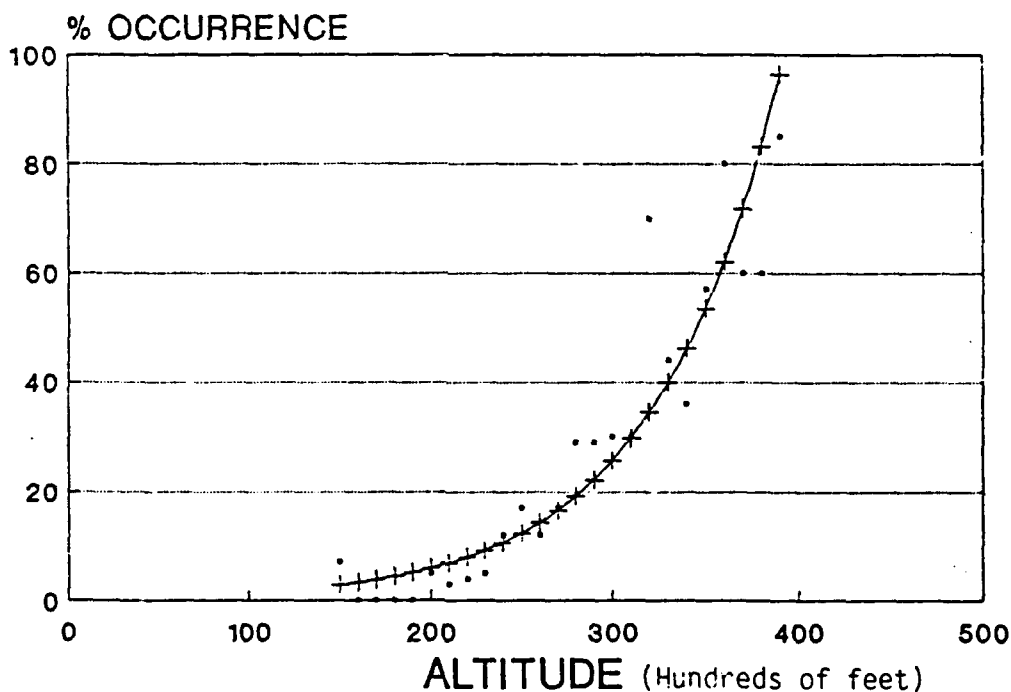


Figure 2. Contrail occurrence vs. altitude. The percent frequency of occurrence increases from near 0% at 15,000 feet to near 85% at 39,000 feet.

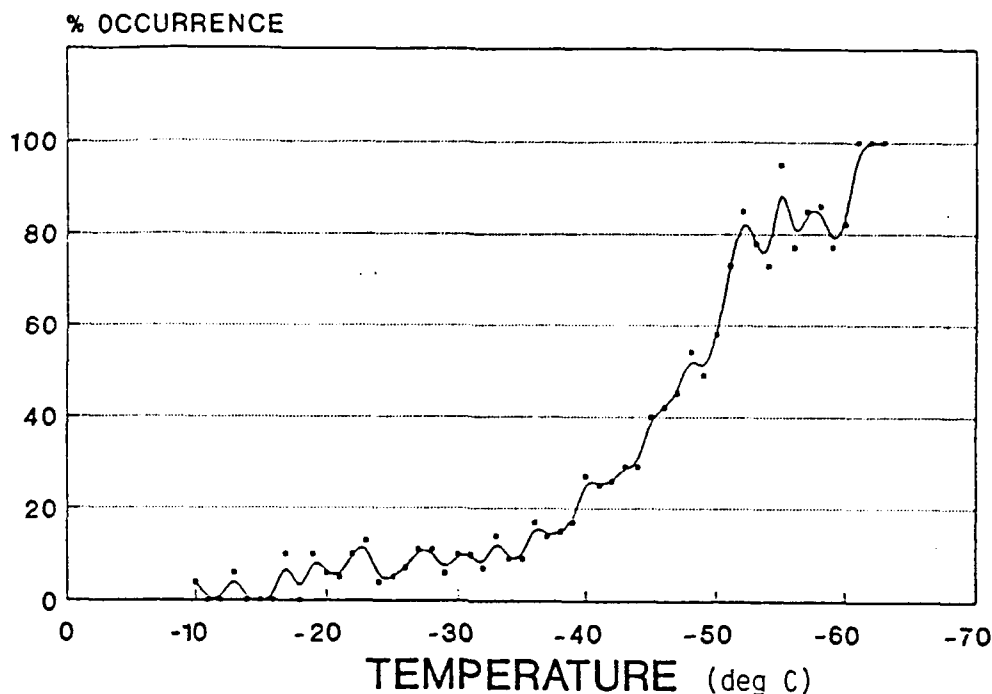


Figure 3. Contrail occurrence vs. temperature. Results of the temperature analysis show a dramatic increase in the percent occurrence from -40 deg C to -51 deg C.

### 3.3 VERTICAL MOTION SENSITIVITY

Correlation between contrail occurrence and vertical motion was closely analyzed with the assumption that synoptic-scale vertical motion is vital to the formation of clouds, and thus to contrails. The sign of the vertical motion was estimated using the 300 mb trough-ridge pattern. Figure 4 represents the sensitivity of contrail formation to vertical motion.

For temperatures warmer than  $-50^{\circ}\text{C}$ , the data show a large increase in the percent frequency of occurrences when synoptic-scale upward motion is present for any given temperature range except when the temperature is  $-50^{\circ}\text{C}$  or colder. This correlation between vertical motion and contrail occurrence indicates the importance of relative humidity to contrail formation.

For temperatures between  $-30^{\circ}\text{C}$  and  $-39^{\circ}\text{C}$ , the 16 percent frequency of occurrence when upward motion is present is only slightly higher than considering only temperature as a forecast parameter. Between  $-40^{\circ}\text{C}$  and  $-45^{\circ}\text{C}$ , a more dramatic increase is seen. Whereas 29 percent of the observations were occurrences when only temperature was considered, percent frequency of occurrence increased to 46 percent when upward motion was incorporated for this temperature range. Similarly, the percent frequency of occurrence for the temperature range between  $-46^{\circ}\text{C}$  and  $-49^{\circ}\text{C}$  increases to 69 percent in areas of upward motion. At or below  $-50^{\circ}\text{C}$ , the vertical motion is not as important a discriminator to contrail formation. Compare the 74 percent of occurrences at or below this temperature to the 84 percent when vertical motion is incorporated. Results indicate any future

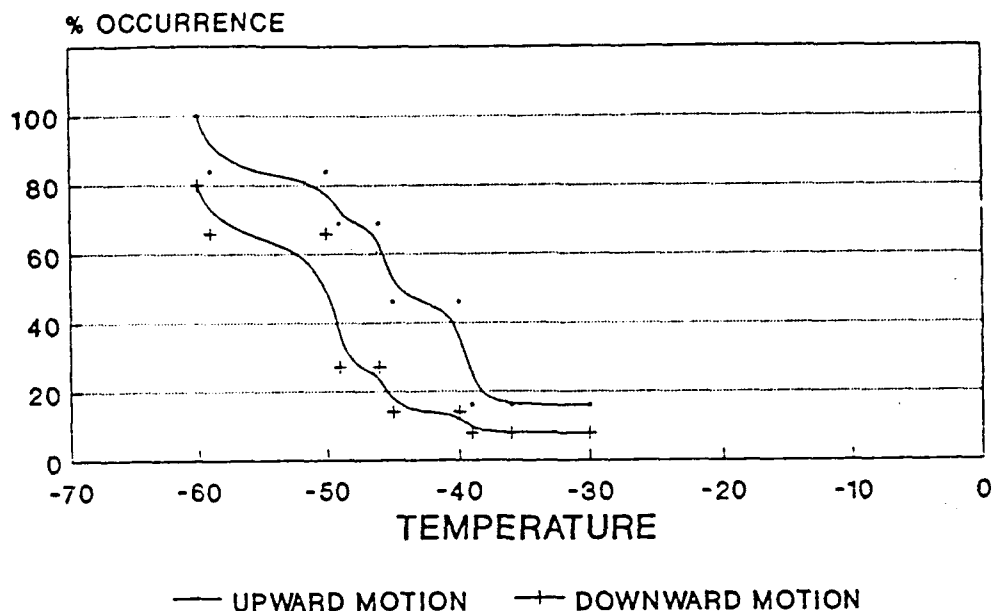


Figure 4. Vertical motion sensitivity. Correlation between contrail occurrence and vertical motion. Increased forecast capability is achieved between -40 deg C and -49 deg C when considering vertical motion.

contrail forecast model must incorporate vertical motion or enhanced relative humidity algorithms.

### 3.4 FORECAST IMPROVEMENTS

For this data set, current contrail forecast techniques used at the Air Force Global Weather Central predicted 24 percent (225 hits/930 chances) of the occurrences and 98 percent (2664 hits/2714 chances) of the non-occurrences. A more reliable technique to forecast contrail occurrences is critically needed to support strategic flight operations. Based on temperature and vertical motion sensitivities of contrail formation revealed in this study, a set of forecast rules was developed.

With the following rules, a 65 percent verification of occurrences (726 hits/1114 chances) and 86 percent verification of non-occurrences (2782 hits/3241 chances) was achieved using the database.

1. If  $T \leq -50^{\circ}\text{C}$ : Forecast contrails.
2. If  $-49^{\circ}\text{C} \leq T \leq -40^{\circ}\text{C}$  and there is upward motion: Forecast contrails.
3. If  $-49^{\circ}\text{C} \leq T \leq -40^{\circ}\text{C}$  and there is downward motion: Forecast no contrails.
4. If  $T \geq -39^{\circ}\text{C}$ : Forecast no contrails.

### 4. CONCLUSIONS

The Strategic Air Command Contrail Formation Study is the first step in a long-term effort to improve contrail forecasting. The data documents the existence of "warm contrails" and clearly indicates any improvements to contrail forecast models must include vertical motion as a predictor in the absence of more accurate relative humidity observations or forecast. Forecast rules developed from this database analysis indicate dramatic improvements in occurrence forecasts. Current procedures verify 24 percent of the occurrences; the rules developed from this study verify 65 percent of the occurrences. Contrail forecasting will remain a vital part of the overall weather support to USAF strategic aircraft. This study along with future efforts to understand contrail formation, will provide improved contrail forecast for the operational community.

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